Defense Technical Information Center Compilation Part Notice

ADP013858

TITLE: Disorientation, Dizziness and Postural Imbalance in Race Car Drivers, a Problem in G-Tolerance, Spatial Orientation or Both

DISTRIBUTION: Approved for public release, distribution unlimited
Availability: Hard copy only.

This paper is part of the following report:

TITLE: Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures [Desorientation spaiale dans les vehicules militaires: causes, consequences et remedes]

To order the complete compilation report, use: ADA413343

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP013843 thru ADP013888

Disorientation, Dizziness and Postural Imbalance in Race Car Drivers, a Problem in G-Tolerance, Spatial Orientation or Both

Frederick E. Guedry, Ph.D., Anil K. Raj, M.D. and Thomas B. Cowin, B.Sc.
The Institute for Human and
Machine Cognition at the
University of West Florida
40 South Alcaniz Street
Pensacola, FL 32501
USA

fguedry@ai.uwf.edu, araj@ai.uwf.edu and tcowin@ai.uwf.edu

Abstract.
On April 28, 2001, Championship Auto Racing Teams (CART) drivers reported experiences of disorientation, dizziness, nausea and blurred vision during practice trials on the Texas Motor Speedway (TMS). Following the practice trials, there were reports of postural imbalance. As a result, the Firestone Firehawk 600 race scheduled for Sunday April 29 was cancelled,; the first time in auto racing history that concerns about driver intolerance to G forces caused a cancellation. The four drivers who did not experience problems had completed less than 20 laps (drive time of 8 min) whereas those reporting symptoms had driven on the track for more than 8 min.

Using track data (maximum average speed in qualifying laps, radius of turns, bank angle of turns), we have calculated the magnitudes of 'gravito-inertial forces" experienced by drivers on a number of speedways in the US. This reveals that drivers experience high G, particularly lateral G (Gy) on most speedways. Other tracks, eg., Dover Motor Speedway, also have steep banks and relatively small-radius turns, but have been raced at lower speeds. Some have banked turns that are steeper than the TMS turns. Calculated G-loads were greatest on the TMS, due to 220-250 mph car speeds. However, considering the semi- reclining posture of drivers, Gz on turns was not in a range that would be expected to produce G induced loss of consciousness (G LOC).

It is suggested that the pattern of visual, vestibular and proprioceptor stimulation contingent upon driver control actions during repetitive laps on the TMS is responsible for the dizziness, disorientation, blurred vision and nausea experienced by the drivers, and onset of adaptation to these conditions induced the post-exposure postural imbalance.

Calculation of tri-axial angular and linear accelerations during two imaginary laps on the TMS at speeds and lap times comparable to those reported are used to compare driver's stimulus conditions to conditions that produce spatial disorientation, nausea, and postural imbalance in centrifuge experiments, in military and commercial aviation and in other modes of modern transportation. Avenues of research necessary for advances in dealing with the problems of drivers, aviators, passengers in modern transportation and even 'dizzy' patients are discussed. A multi-national approach is necessary for near-term advances.

Background. On Friday, April 27, 2001, two drivers were unable to complete practice laps on he Texas Motor Speedway (TMS) due to disorientation, dizziness, nausea and blurred vision. Another driver reported being unable to walk away from his car for several minutes after practice laps on April 28. Later at a dinner meeting, 21 of the 25 drivers scheduled to start the Firestone Firehawk 600 on Sunday April 29 expressed concern about these symptoms. As a result, the race was cancelled; the first time in the auto-racing world that concerns about physiological tolerance caused a cancellation. Based on comments by the doctor for the Championship Auto Racing Team (CART), the media announced to the nation that the problem was G-induced Loss of Consciousness (G-LOC), a well known problem in Aerospace Medicine (7). The solution was for drivers to go through USAF pilot training on combating GLOC.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

Converging circumstances precipitated this historic cancellation. Beginning in 1998, improvements that were made to the track and to racing engines permitted higher sustained speeds. Advances in CART car engines and drive trains made these cars very fast; in fact CART cars may be the world's fastest team cars. Formula One cars have greater acceleration (0 to 100mph in 2 sec, compared to 0-100 in 4.2 sec for CART cars) but lower top speed. Figure 1 depicts TMS.

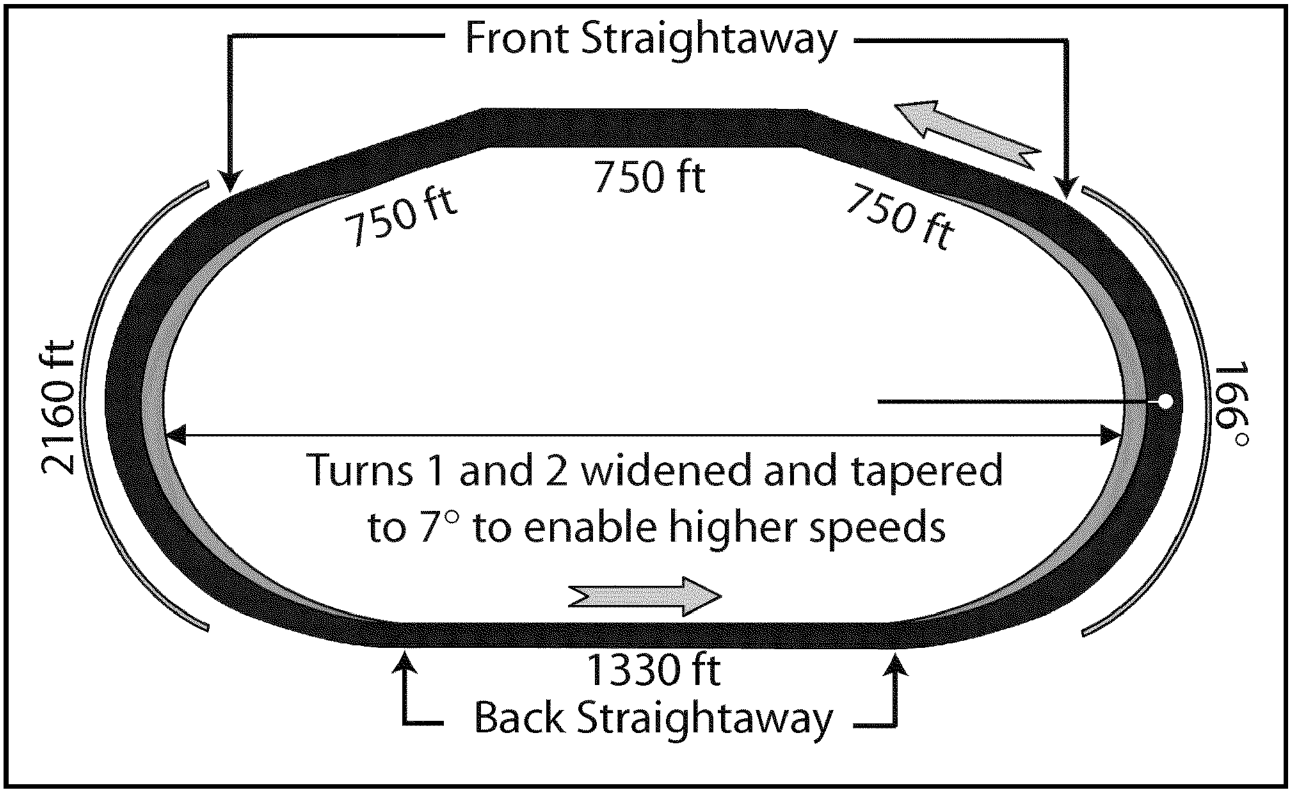

Figure 1. Sketch of Texas Motor Speedway (TMS) viewed from above. The Front 'Straightaway' is 2250ft (three 750 ft segments) in length, and the Back Straightaway is 1330 ft in length. The bank of Turn 1 and Turn 2 is 25deg., but, to enable higher speeds, Turns 1 and 2 were widened (near the infield) where the bank was decreased to 7deg..

At the time of the TMS problem, a paper by Gresty and colleagues (22) described passenger problems in Tilting Trains. Active suspension systems in trains operating in Switzerland, France and Germany permitted higher speed on curves. The active suspension system kept the Gravito-inertial Force (GIF) vector aligned with the 'upright' dimension of the coach, but the interior of the coach is the 'visual vertical' for passengers. Passengers viewing the passing countryside became Train Sick. Gravity sensors responding to the GIF were in conflict with the view of the countryside. Note that train tracks are banked very little; the turn radius of train tracks is sufficiently large to prevent high lateral G even at speeds of 150 km/hr.

Returning to the TMS, the banks on the turn at each end of the 1.5 mile oval are 24deg.. Because pilots routinely bank 60deg. in 2G turns to avoid slips and skids, GLOC seemed unlikely. However, we learned from a friend (Phil Babbcock) who restores classic cars and also participates in 'road' races, that drivers make controlled skids in cars which are especially designed to make high speed turns 'safely'. Internet sources (e.g., www.nascar.com, www.texasmotorspeedway.com) provided sufficient information, including lengths of straightaways (one of which includes two turns), turning radius (750 ft.) on the two 24deg. banked turns, and the top average lap speed (245.4mph) to estimate TMS G vectors. On the TMS 24deg. turns, 5G+ (lateral) would be experienced.

Early in 2001 in cool weather, an experienced driver tested the improved TMS, concluding that drivers would like the improved TMS, and that they should be able to drive full throttle around the 1.5 mile oval. However the average speed in test runs (224mph) was less than speeds on 27 April; the temperature was lower, and the number of consecutive laps in any one test run may have been less than 20.

On April 27, CART cars were completing laps in 22-25 seconds so that 20 laps were completed in about 8 minutes. Thus 21 drivers who completed 20 or more laps reported dizziness, and the 4 drivers who did not experience dizziness drove less than 8 minutes.

Was G-tolerance the problem? These very experienced drivers had never reported problems before. High G-loads are common in race cars. The structure, tires, suspension system and the semi-reclining posture of drivers are designed to obtain a low profile to prevent overturning during high lateral G. Speed reduction during full throttle during turns would result from the controlled skids (scrubbing) that experienced drivers often use in turns. Perhaps the media were right. Perhaps with a 24deg. bank, head-to-seat G is sufficient to produce occasional G-LOC. However, the head-to-seat component that threatens GLOC is much less as illustrated in Figure 2a.

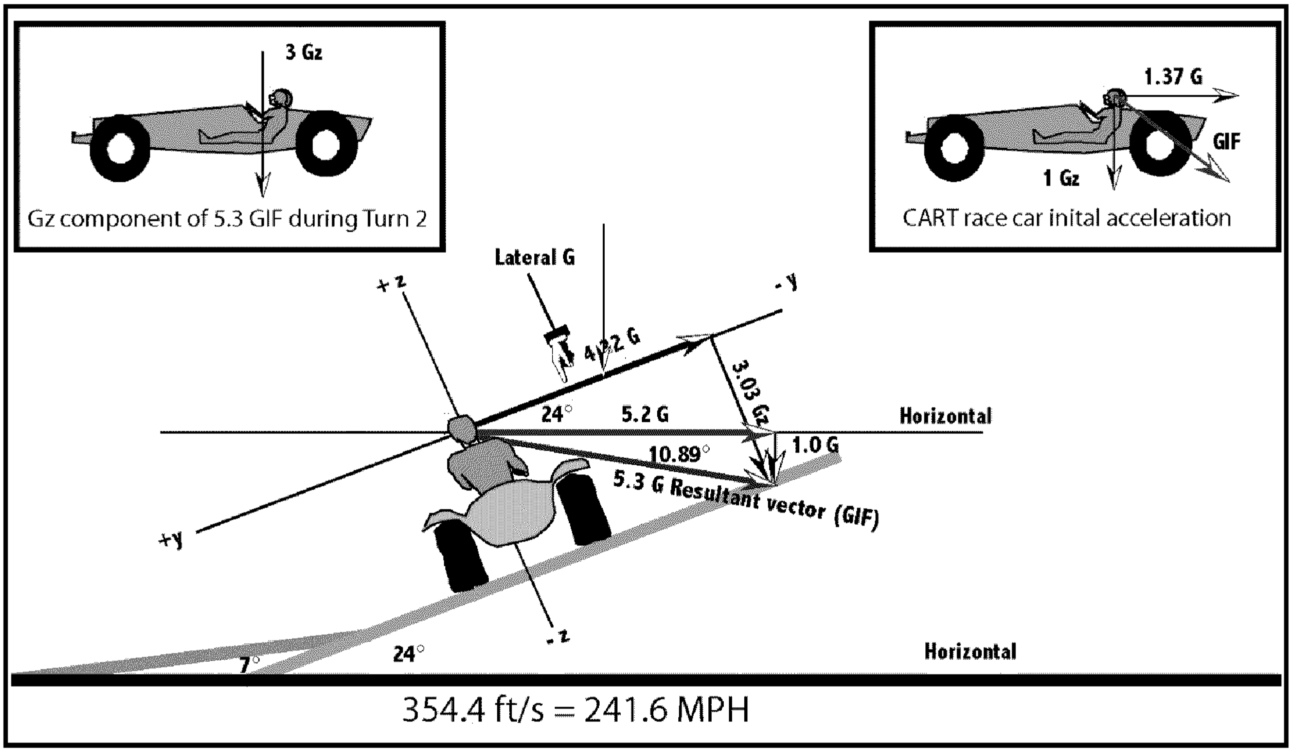

Figure 2a. At 240 mph (turn rate 27deg./s on a radius of 750ft), the driver's perceived centrifugal force is 5.2 G. The GIF components on the y- and z- axes of the head are 4.3Gy and 3.0Gz. If the driver steers high on the last segment of the front 'straightaway' and eases throttle while descending to the lower lane with 7deg. bank of Turn 1, the suspension system could level the driver's y-axis which would yield 1.0 Gz and 5.2Gy. While 'cutting the corner', the radius of turn may be increased to 800+ft which would reduce Gy. Considering the driver's posture (upper left panel), Gz=0.0 on the legs and less than 1.0G on the trunk. Upper right panel describes initial acceleration on the unbanked front straightaway.

Aviation Medicine and Race Car Drivers. In the 1940's and 50's, the US Air Force and US Navy conducted centrifuge studies to estimate how much G-tolerance could be improved by supine and prone pilot posture in high performance aircraft. Subjects were exposed to high Gx in supine and prone postures in centrifuge gondolas. Subjects exposed to 9+ Gx did not experience G-LOC, but there were after-effects. In Pensacola, a volunteer became dizzy shortly after exposure to 10Gx, and was bed-ridden for about two weeks due to dizziness and postural imbalance which persisted in diminished form for about 2 years. Other similar after-effects have been reported from time to time. For example at the Navy Johnsville centrifuge, a volunteer experienced persisting dizziness and postural imbalance following 12 Gx exposure. More recently, Groen and colleagues (24), in the Netherlands, reported dizziness and postural imbalance in some subjects following one to two hour duration of 2Gx-3Gx.

Because aircraft do not expose pilots to high lateral G, their effects have not been not well-established. However, lateral G is of concern because internal organs such as the heart, lungs, kidney contents, stomach contents will be displaced relative to one another due their different specific gravities. Moreover, the rate at which the CNS receives G-induced signals from internal organs is sufficient to play a significant role in perception of verticality (1, 51, 52).

Tilt Perception. Since the observations of Mach (44, 45), first reported in 1873, the fact that lateral G produces an erroneous perception of roll tilt on centrifuges has been documented many times. The dynamics of tilt perception are very important in attempting to model the perceptions of race car drivers and of pilots in aircraft. The GIF tilts in roll approximately 79deg. during 5G lateral (Gy), but roll perception (subjects seated upright relative to gravity) lags far behind the physical stimulus (8, 13, 19, 20, 54, 62). In darkness on a centrifuge, the time constant (TC) of tilt perception is about 15 seconds. In a lighted room, perceived tilt (on average) is midway between the 'visual vertical' and the GIF (65). Assuming roll-tilt perceived by a driver is reduced by 75% due perceptual lag, perceived roll would be about 20deg. as illustrated in Figure 2b, less than the 79deg. GIF tilt (Figure 2a). Figure 2b also illustrates (upper right panel) estimated 8deg. pitch perception of a Formula One (higher acceleration) car driver during 2.5 sec of starting acceleration, based on simulation of aircraft catapult launch (10).

There are well-known individual differences (e.g., some individuals are influenced by the visual framework and others are more influenced by the GIF). The incidence of motion sickness in motion simulators and in various forms of transport seems to be higher in people strongly influenced by the Visual Field than in those more influenced by the GIF (42a, 42b). Individuals with Motorists Disorientation Syndrome are sometimes helped by devices that block their lateral view (56). Research into the Visual-Field dependence of drivers may be interesting.

In everyday life, a lag in tilt perception is unacceptable. Normal postural dynamics require very quick detection of head and body tilt, even in darkness. Patients without this ability are in serious trouble (2). Quick detection of roll-tilt, for example, depends upon a roll signal from the semicircular canals and concordant messages from the otolith system and other gravity sensors (17, 29).

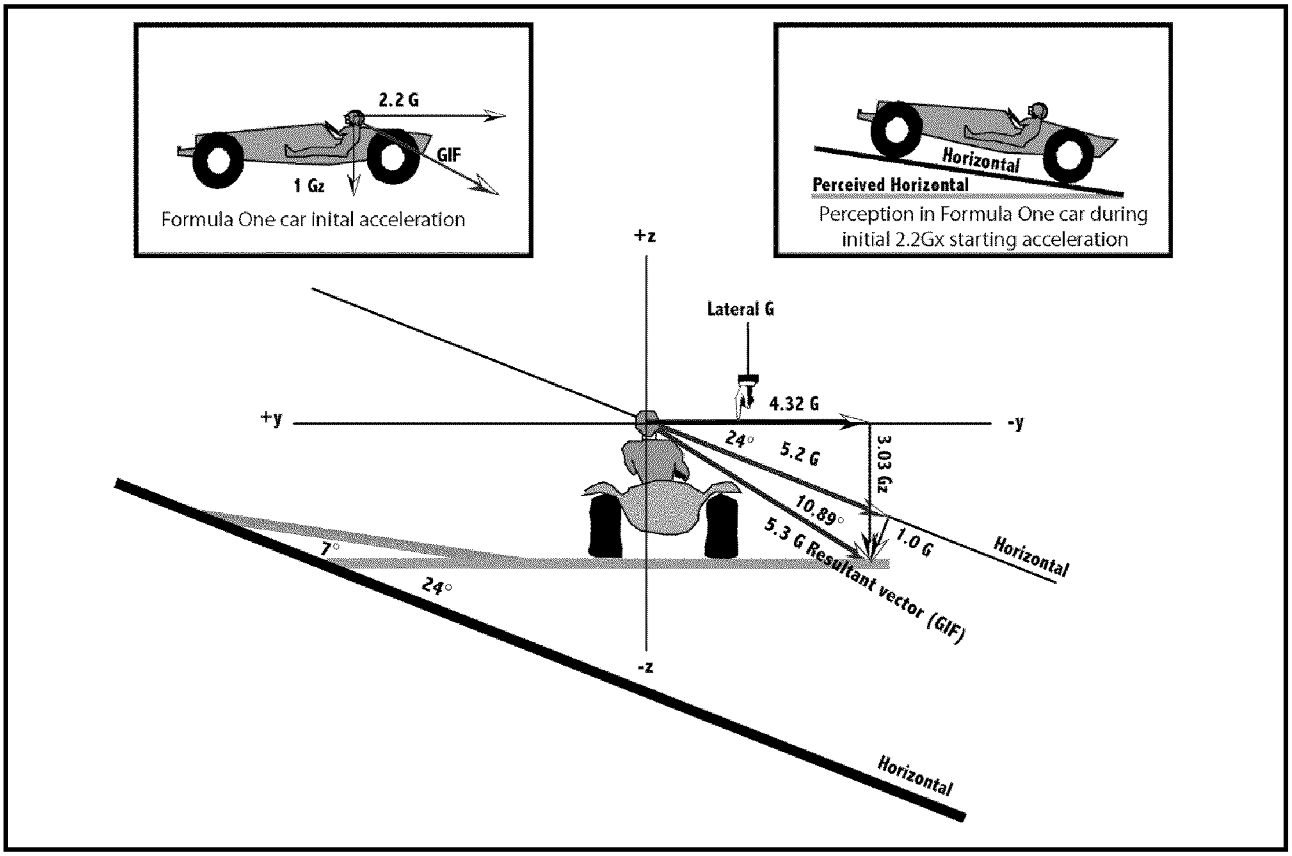

Figure 2b. Although the Gif is Tilted 79deg. relative to gravity on the 24deg. bank of Turn 2, lag in tilt perception could yield perception of zero body tilt and a horizon tilt less than GIF tilt. Upper right panel conceptualizes a Formula-one car driver during 2Gx starting acceleration on the 5deg. bank of the Front straightaway. GIF Pitch Tilt is 60deg., but due to perceptual lag, 10deg. pitch-up tilt of body and horizon is illustrated, based on findings of Cohen et al (10). In carrier catapult launches, pilots experience 4Gx for 3.2s, and in darkness the pitch-up perception persists for about 20s which has resulted in controlled flight into the ocean.

A model capable of predicting the perceptions of race car drivers and pilots will be very complex. An interesting approach to modelling taken by Jan Holly assumes that the CNS is a perfect processor of angular and linear information provided by the semi-circular canals and otolith systems (39, 40). Using estimates of lateral G calculated from car speed and turn radius, Holly has developed a model of turn and tilt perception during 10 consecutive laps on the TMS with the interesting result illustrated in Figure 3. The graph in Figure 3 represents roll-tilt perception extracted from the output of a fully three-dimensional (3 linear, 3 angular) simulation.

While inspecting Figure 3, keep in mind that drivers are focused on other cars (front and rear), path and slope of track, but they also are aware of fuel and engine gauges, body temperature in cooling vests, pit stops, and bodily needs during 600 laps. Figure 3 shows predicted roll tilt perception for a subject who is focused on indicating perceived tilt. It illustrates false data reported to the Central Nervous System (CNS) by non-visual motion and tilt sensors that must be overcome with visual information and training (15, 26, 48).

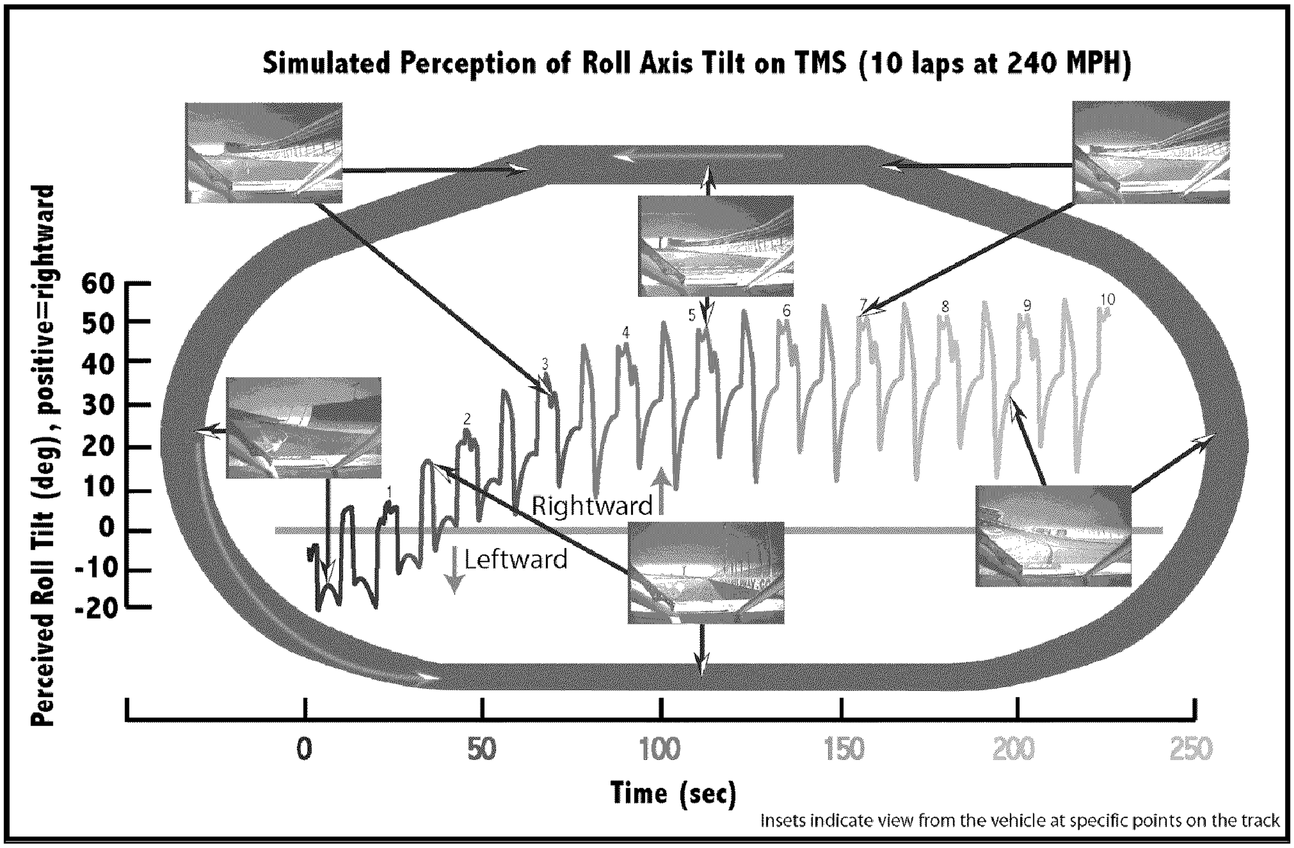

Figure 3. This graph of the output of Holly's model which included perceptual time constants based on the lag in perception of verticality when the GIF tilts relative to an upright subject, and perception of rotation as influence by velocity storage (9).

Models can be used for: a) estimates of effects of consecutive laps which can be compared with reports from drivers; b) predictions of particularly dangerous portions of highways could be compared with Highway accident records; c) selecting strategies in races; d) evaluating race track design, etc.

Dizziness without High G exposure. Dizziness, blurred vision, stomach queasiness and postural imbalance are common during and after rides in land, sea and air vehicles, in amusement park and laboratory devices, including some in which the subject is stationary. Moving visual fields can produce perceived whole-body motion (49), motion sickness and postural imbalance after-effects, viz., I-max, flight and ship motion simulators (6, 21, 42 a). Many motion platforms provoke a high incidence of all of these symptoms with G-forces no greater than those encountered in walking and running (15, 25, 28, 34). In fact these symptoms in relatively immobile individuals bring over 100,000 patients each year in the US alone to Otolaryngologists and Neurologists. Watt and colleagues (66) produced motion sickness in subjects who were standing erect and actively oscillating the upper body and head 'en bloc' in yaw for 5 or 10 minutes. During the initial days on orbit, astronauts in 'zero G' restrict head movements by moving head and trunk 'en bloc' to avoid unnecessary head movements which produce 'space sickness (55); brief 'zero G' during parabolic flight produces motion sickness (41b). Following orbital missions, astronauts have postural imbalance that sometimes lasts for many days (5, 57). Alcohol intake (>4 ounces) produces blurred vision and postural imbalance for about 4 hours after consumption (32). Certainly some CART drivers were exposed to conditions that tend to produce spatial disorientation, dizziness and nausea, but why the problem on the TMS on April 27, 2001? Some possible answers based on Aviation Medicine research follow.

G-load change frequency and Motion Sickness. The TMS has two 24deg. banked turns, each 166deg. in length, and two turns in the Front Straightaway each 14deg., totalling 360deg./lap. If lap time is 22 seconds, the frequency of substantial G change experienced is 0.18cps. This happens to be a very provocative stimulus frequency for motion sickness (3, 11, 14, 28, 42a). Recordings of tri-axial accelerometers made during several laps around the TMS will permit better comparison with the literature on stimulus frequency and motion sickness incidence.

Centrifuge Deceleration. Deceleration of a swinging gondola centrifuge produces a disturbing, frightening perception of pitch change (nose down) coupled with pitch tumble velocity much too great for the perceived change in pitch position (29, 38). Paradoxical perceptions and nausea are common in situations that generate conflicting information about motion from different senses (38). When a race car transitions from the 24deg. slope of turn one to the 5deg. slope of the Back Straightaway, the driver experiences angular deceleration coupled with changing GIF roll. Will this transition produce effects similar to centrifuge deceleration?

No, for several reasons: a) The magnitude of the angular deceleration involved is low because the maximum angular velocity in the turn is only about 27deg./s. b) If the angular velocity were greater, the answer is still no, because the Time Constant (TC) of responses produced by the lateral semicircular canals is about 15 seconds, and so the deceleration would be perceived as stopping the turn. (27). c) The earth-fixed visual field, non-visual motion and tilt sensors and active control by the driver combine to yield perceptions sufficient for accurate control of motion.

These factors can be evaluated fairly well on a few existing multi-axis centrifuges with ‘virtual reality’ capabilities in the gondola, but an important condition that cannot be simulated on existing centrifuges is angular deceleration without loss of forward speed. On centrifuges, the sudden drop off in centripetal acceleration as angular deceleration begins produces “pitch forward” otolith and proprioceptive stimulation soon followed by cross-coupled canal-stimulation indicating forward tumble in a subject whose restraint system is discomforting during pitch forward perception (29, 38). Aircraft and race cars frequently increase forward speed as they come out of High G turns, in which information from the visual-vestibular-proprioceptor systems and active vehicular control, in combination, is sufficient for control of motion.

Race Track Research. Figures 4a and 4b are sketches made from an overhead perspective of the TMS Oval, conceptualising Laps 1 and 2 of a race. Think of the TMS as a very large complex centrifuge with a tri-axial gondola at the end of the arm. The gondola contains sets of triaxial linear and angular accelerometers, and a recording system for several perceptual and physiological responses. A large earth-fixed visual display containing large and small 3-dimensional objects can be made visible or it can be with-held. When visible, the relative movement of the display can be recorded and time-locked to the responses of the subject and to the linear and angular accelerations experienced by the subject.

In Lap 1, the car begins accelerating at the starting line in the Front Straightaway so that speed is increasing to a point in Turn 1 conceptualised in Figure 4a. Figure 4b illustrates Lap 2, a “full throttle” lap in which speed changes are due to controlled skids during which speed is “scrubbed off”.

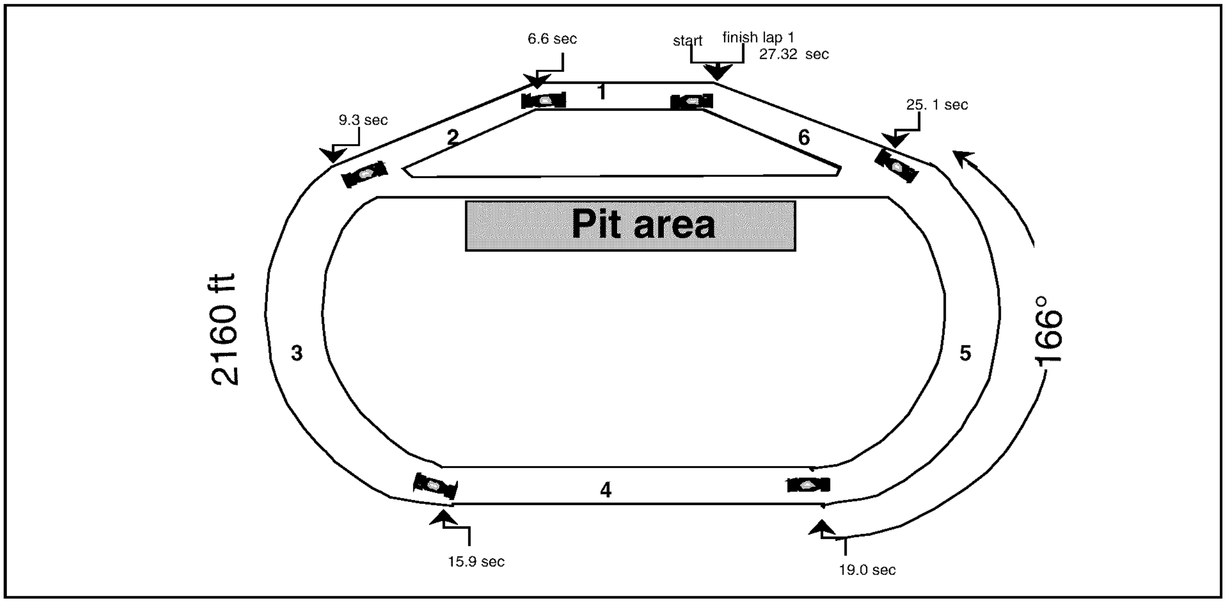

Figure 4a. Assumptions for Lap 1: Starting acceleration of CART cars is 0 to 100mph in 4.2 sec (1.08Gx); speed is 352ft/s (240mph) during Turns 1 and 2; speed on back straightaway is 250mph. Radius of turns 1 and 2 is 750ft.

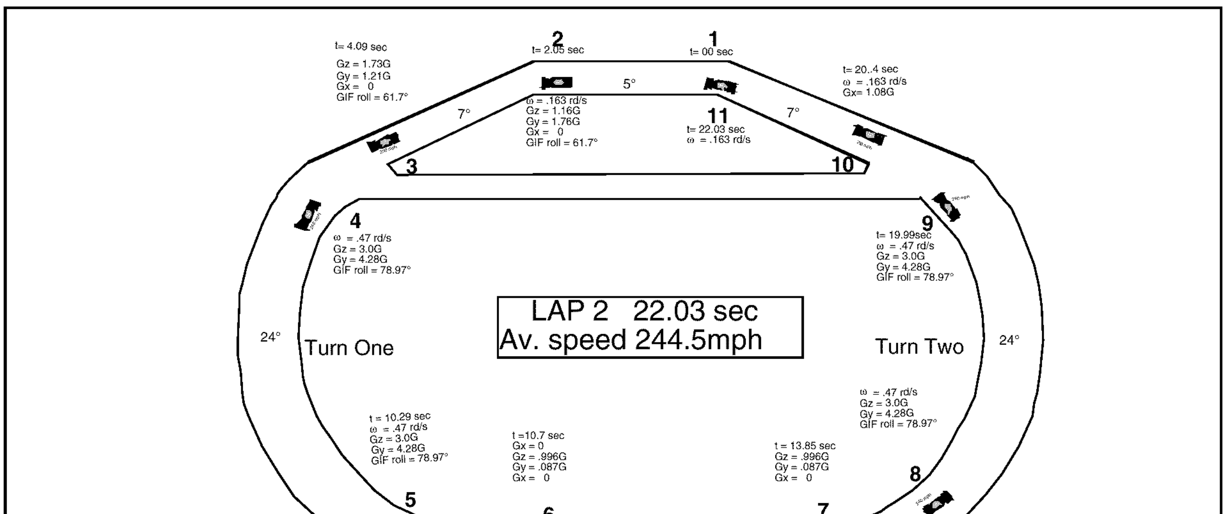

Figure 4b. As lap 2 begins at point one, speed is 250mph. Assume that the Front “straightaway” is driven as a large radius (2250ft) turn with a 5deg. bank. At point 2, the 7deg. bank begins which changes Gz and Gy. At point 4, the bank increases to 24deg. and the turn radius is reduced to 750 ft (Gy=4.3G, Gz=3.0G) so that speed is scrubbed off to 240mph. Between points 5 and 6, the car accelerates at 1.08Gx to 250mph.

Now consider some of the capabilities of this track as a centrifuge:

Dynamic Visual Acuity

What is the influence of an earth-fixed visual background on visual acuity for near objects during self-motion at 20-90 mph and at speeds greater than 200 mph? Studies in which this question was pursued using a 2D visual display on which a “near” moving object was viewed against an “earth-fixed background” on the same

flat display indicate that dynamic visual acuity for the "near" object is degraded when a stationary background is visible. However, inferential evidence suggests that visual pursuit (36,41) and dynamic visual acuity for a near object viewed against a more distant earth-fixed background is better than when no background is available (35).

What are the short- and long-term effects of exposure to cyclic sustained complex angular and linear acceleration on every system of the body? Note the interesting transition from perceived right tilt in the early laps to left tilt in later laps in a total of 10 laps illustrated in Figure 3.

Disorientation-error Aircraft Accidents (DAA).
The typical analysis of DAA centres on available visual reference, distraction from cockpit instruments and GIF. The direction of the GIF is usually accepted as the pilot's erroneous perception of aircraft attitude when visual reference is absent (4, 10, 63, Paper 10 of this meeting). While this is a useful "first guess", known lags in verticality perception must be better understood. A model that predicts verticality perception during sequences of complex changes in the GIF will be of great value.

Feasibility of Race Track Research.
The TMS and other race tracks seem to be available for trial runs by interested individuals on non-racing days. Four laps at speeds 140-160mph can be driven as a passenger (61). A triaxial linear and angular acceleration package with recording system can be installed in a Team Texas NASCAR style car. These cars are used for "tourists" and for racing schools. Alternatively, a car owned by an individual or research institute can be equipped with sensor and recording packages for linear and angular accelerations, visual scene and perceptual and physiological responses. The cost of purchasing and operating a very good car, including maintenance, will probably be less than the cost of operating a large multi-axis centrifuge.

Summary and Conclusions.

1. The problem reported by drivers on 27 April was probably not due to G-LOC. The most probable cause was the stress and fatigue that is generated when whole-body motion is actively controlled in spite of mixed sensory messages about the state of self-motion and self-tilt.

2. Drivers experience cyclic high G for several hours during races. Track races are run on ovals like the TMS, some shorter some longer with banks on the turns some less than some greater than those of the TMS. All turns are counterclockwise (as viewed from above). Thus track races are similar to a very large centrifuge except for straightaways between turns and bank angles that do not maintain the head-to-seat GIF alignment that is present in swinging gondola centrifuges and in aircraft during co-ordinated turns. During turns on track races, the driver experiences lateral G similar to centrifuge subjects who remain upright relative to gravity or in some fixed position relative to gravity (8, 12, 16, 20, 30). Each of these different fixed positions on a centrifuge yields different roll and pitch perception dynamics. On swinging gondola centrifuges, subjects perceive roll even though the roll plane component of the GIF remains aligned with the head-to-seat axis (38, 16, 64).

3. Drivers may not have reported problems before 27 April for the same reason pilots withhold information from Flight Surgeons. Pilots want to retain Flight status, and drivers want to continue racing. Discussion with the two drivers who were unable to complete practice laps prompted other drivers to admit similar symptoms. Those who did not experience similar symptoms may have been showing solidarity with the affected drivers or have been concerned about racing in conditions where anyone could suffer similar symptoms. The annual income of top drivers is millions of US dollars and Euros.

4. The cooling vest worn by drivers suggests that a vest containing "tactors" may be feasible. Pilots wearing tactor vests activated by attitude and other instruments can maintain control of aircraft while blindfolded or under other degraded visual conditions (46a, 58, 60). Drivers could be alerted to the position of overtaking cars, information that would supplement information from the spotter who communicates with the driver.

5. Although a model to predict the spatial orientation perceptions will necessarily be very complex, it will be no more complex than a model that will predict responses of an individual in every day life activities. Individuals with disorders of the spatial orientation system perceive unreal tilts and movements that are very disturbing, and also very perplexing to the physician.

6. Drivers are typically medium height or less, trim individuals who maintain physical fitness regimens. However, considering the long sustained cyclic G experienced by drivers, the incidence of disorders that potentate dizziness, such as Benign Positional Vertigo and neck injury (2, 47), should be carefully monitored.

7. The typical analysis of Disorientation-error Aircraft Accidents centers on available visual reference, cockpit distraction from instruments and GIF. The direction of the GIF is usually accepted as the pilot's erroneous perception of aircraft attitude when visual reference is absent. A model that predicts perception of verticality during sequences of complex changes in the GIF will be of great value in analysis of aircraft accidents and driver challenges in car races.

8. Models consistent with: a) dynamics of the sensory systems critical to spatial orientation and control of motion b) anatomy and neurophysiology and c) quotidian "functionality" (37, 59) have been critical to advancing understanding of spatial orientation perception and the problems of patients. Information from research in which responses have been measured in particular time segments of the "frequency domain" is a necessary step toward modelling three-dimensional path-of-movement perception during 10 or 20 laps in which two straightaways (one with two 14deg. turns in it) are interposed between two 166deg. turns. Description of perception and dynamic visual acuity during early, middle and late sequences of laps in a total of 600 laps on the TMS could provide empirical data for testing models of responses during complex activities during long time periods.

Acknowledgements. The authors thank Jan Holly, Department of Mathematics, Colby College, Waterville, ME. (jeholly@colby.edu) for substantial contributions to this paper, Lynda Jewett for administrative assistance and Ken Ford (kford@ai.uwf.edu) and Angus Rupert (arupert@namrl.navy.mil) for encouragement and support during the preparation of this manuscript.

References.

1. Balaban, C.D. Vestibular autonomic regulation (including motion sickness and the mechanism of vomiting). Current Opinion in Neurology.12 29-33.

2. Baloh, R.W. and Halmagyi, C.M., Editors, Disorders of the Vestibular System. Oxford University Press, 1996.

3. Benson, A. J. (1974). Modification of the response to angular accelerations by linear accelerations. Handbook of Sensory Physiology; Vestibular System Part 2: Psychophysics and Applied Aspects and General Interpretations, H. H. Kornhuber (Ed.), Heidelberg, Springer-Verlag. 281-320.

4. Benson, A.J. "Somatogravic Illusion Revisited." Air Clues, pp. 96-99, March 1988.

5. Black, F.O., Paloski, W.H., Reschke, M.F., Guedry, F.E., Anderson, D.J. (1999) Disruption of Postural readaptation by inertial stimuli following Space Flight. Accepted for publication. J. Vestibular Res.

6. Bles W., Kapteyn T.S.. Circular vection and human posture I. Does the proprioceptive system play a role? Agressologie. 1977;18:325-8.

7. Burton, R.R., Cohen, M.M., and Guedry, F.E., G-induced loss of consciousness. (A panel presentation of the Science and Technology Committee, 1986 Annual Scientific Meeting of the Aerospace Medical Assn.) Aviat. Space Environ. Med., 59:1-39, January 1988.

8. Clark, B. and Graybiel, A. (1966). "Factors contributing to the delay in the perception of the oculogravic illusion." *American Journal of Psychology*, 79:377-388.

9. Cohen, B., Henn V., Raphan, T., and Dennet, D. (1981). Velocity storage, nystagmus, and visual-vestibular interactions in humans. *Ann NY Acad Sci*, 374:421-433.

10. Cohen, M. M., Crosbie, R. J. and Blackburn, L. H. (1973). "Disorientating effects of aircraft catapult launchings." *Aerospace Medicine*, 44(1):37-39.

11. Correia, M. J., and Guedry, F. E. (1966) Modification of vestibular responses as a function of rate of rotation about an earth- horizontal axis. Acta otolaryng., 62:297-308.

12. Correia, M. J., Hixson, W. C. and Niven, J. I. (1968). "On predictive equations for subjective judgements of vertical and horizon in a force field." *Acta Otolaryng. (Stockh.)*, Suppl. 230.

13. Curthoys, I. S. (1996) The delay of the oculogravic illusion. Brain Research Bulletin Volume 40, Numbers 5/6.

14. Firman, J.M. and Schor, R.H. (2001) Semi-circular canal and otolith organ interactions during off-vertical rotation in humans. JARO 2/1:022-030.

15. Fregly, A.R., & Kennedy, R.S. (1965). Comparative effects of prolonged rotation at 10 RPM on postural equilibrium in vestibular normal and vestibular defective human subjects. Aerospace Medicine, 36(12), 1160-1167.

16. Glasauer, S. (1992) Das zusammenspiel von otolithen und bogengängen im wirkungsgefüge der subjektiven vertikale {Doktor-Ingenieurs}. Lehrstuhl für Nachrichtentechnik der Technischen Universitat München.

17. Grant, J. W.; Huang, C. C.; Cotton, J. R. (1994) Theoretical mechanical frequency response of the otolithic organs. *J Vestib. Res.* 4(2):137-151.

18. Gray, R. F. and Crosbie, R. J. (1958) Variation in Duration of Oculogyral Illusions as a function of radius of turn. U.S. Naval Air Development Center, Aviation Medical Acceleration Laboratory, Johnsville, Pa. Report No. NADC-MA-5806 of 22 May 1958.

19. Graybiel, A. and Clark, B. (1965). Oculogravic illusion as an indicator of otolith function. *Aerospace Medicine.* 36(12):1173-1181.

20. Graybiel, A. and Brown, R. (1951). The delay in visual reorientation following exposure to a change in direction of resultant force on a human centrifuge. *Journal of General Psychology,* 45:143-150.

21. Gresty, M.A. Spatial Orientation. (1996) Brain Research Bulletin Volume 40, Numbers 5/6.

22. Gresty, M.A., Neimer1, J., Eskiizmirliler, S., Ventre-Dominey, J., Darlot, C., Luyat, M., Gresty, M. A. and Ohlmann, T. (2002) Trains with a view to motion sickness. Current Opinions in Neurology.

23. Gresty, M.A. and Ohlmann, T. (2002) Spatial Disorientation: The Fundamental Theory. Conmtemporary Psychology of Cognition

24. Groen, E., De Graaf, B., Bles, W., Bos, J. (1996) Ocular torsion before and after 1 hour centrifugation. Brain Research Bulletin Volume 40, Numbers 5/6.

25. Guedry, F. E. (1999) The Pensacola rotating room experience. Invited presentation to Artificial Gravity Workshop, League City, Texas, Feb 14.

26. Guedry F.E., Jr. (1964) Visual control of habituation to complex vestibular stimulation in man. Acta Otolaryngol (Stockh) 58:377-389.

27. Guedry, F.E., (1974) Psychophysics of vestibular sensation. In: Handbook of Sensory Physiology, Vol. VI (H.H. Kornhuber, Ed.) New York/Heidelberg/Berlin:Springer-Verlag, Pp 1-154.

28. Guedry, F.E., (1991) Motion sickness and its relation to some forms of spatial orientation: Mechanisms and theory. In Motion Sickness: Significance in Aerospace Operations and Prophylaxis. AGARD-LS-175, (2): 1-30.

29. Guedry, F.E., (1992) Perception of motion and position relative to the Earth: An overview. In B Cohen, DL Tomko, FE Guedry, Eds., Sensing and Controlling Motion, New York: Annals of the New York Academy of Sciences, 656:315-328.

30. Guedry F.E. (1996) Spatial orientation perception and reflexive eye movements. A perspective and some clinical implications. Brain Res.Bull., 40:505-512.

31. Guedry F.E., & Benson A.J. (1978) Coriolis Cross-coupling Effects: Disorienting and Nauseogenic or Not? Aviat.Space Environ.Med., 49(1):29-35.

32. Guedry, F.E., Gilson, R.D., Schroeder, D.J., and Collins, W.E., (1976) Some effects of alcohol on various aspects of oculomotor control. Aviat. Space Environ. Med., 46:1008-1013.

33. Guedry, F.E., and Correia, M.J., (1978) Vestibular function in normal and in exceptional conditions. In: "Handbook of Behavioral Neurobiology" (R.B. Masterton, Ed.) New York: Plenum Publishing Co.

34. Guedry, F.E., and Graybiel, A., (1962) Compensatory nystagmus conditioned during adaptation to living in a rotating room. J. Appl. Physiol., 17:398-404.

35. Guedry, F.E., Lentz, J.M., and Jell, R.M., (1979) Visual-vestibular interactions: I. Influence of peripheral vision on suppression of the vestibulo-ocular reflex and visual acuity. Aviat. Space Environ. Med., 50:205-212, 1979.

36. Guedry, F., Davenport, K., Brewton, C. and Turnipseed, G. (1979) The pendular eye-tracking test under two viewing conditions. NAMRL 1257, January.

37. Guedry, F.E., Rupert, A.H., Reschke, M.F. (1998) Motion sickness and development of synergy within the spatial orientation system, a hypothetical unifying concept. Brain Res.Bull.,Vol 47, no. 5, pp475-480.

38. Guedry, F. E., Rupert, A. H., McGrath, B. J. and C. M. Oman (1992). "The dynamics of spatial orientation during complex and changing linear and angular acceleration." *Journal of Vestibular Research,* 2:259-283.

39. Holly, J. E. (2000) Baselines for three-dimensional perception of combined linear and angular self motion with changing rotation axis. J. Vest. Res., 10, 162-178.

40. Holly, J. E. (1997) Three dimensional baselines for perception of self-motion during acceleration and deceleration on a centrifuge. J. Vest. Res., 7, 45-61.

41. Hood, J. D. (1975) Observations on the role of the peripheral retina on the execution of eye-movements. ORL, 37, 65-73.

41b. Kellogg R.S., Kennedy R.S., & Graybiel A. (1965) Motion Sickness Symptomatology of Labyrinthine Defective and Normal Subjects During Zero Gravity Maneuvers, Aerosp.Med., 36:315.

42a. Kennedy, R.S. Hettinger L.J., and Lilienthal, M. (1990) in G.H. Crampton, Ed. Motion and Space Sickness. CTC Press, Boca Raton, FL, pp. 317-341.

42b. Kennedy, R.S., Dunlap W., Fowlkes, J.E. (1990) Pediction of Motion Sickness Susceptibility. in G.H. Crampton, Ed. Motion and Space Sickness. CTC Press, Boca Raton l., pp179-215.

43. Lansberg, M. P., Guedry, F. E. and Graybiel, A. (1965). "The effect of changing the resultant linear acceleration relative to the subject on nystagmus generated by angular acceleration." *Aerospace Medicine*, 36:456-460.

44. Mach, E. (1902). The Analysis of Sensations. Republication of fifth edition (1959). Tr. by C.M. Williams 1902. New York: Dover 1902.

45. Mach, E. (1873) Physikalische Versuche uber den Gleichewichtsinn des Menschen. S. B. Akad. Wiss. Wien. 45:124-140.

46. McGrath, B.J. (2000, Aug) Tactile Instrument for Aviation. NAMRL Monograph 49, Naval Aerospace Medical Research Laboratory, Pensacola, FL 32508-1046.

46. McGrath, B. J., Guedry, F. E., Oman, C. M., and Rupert, A. H. (1995). "Human vestibulo-ocular response during 3Gz centrifuge stimulation." J. Vest. Res., 5(5):331-347.

47. Mergner T, Huber W, Becker W. Vestibular-neck interaction and transformation of sensory coordinates. J Vestib Res. 1997;7:347-67.

48. Mergner T and Rosemeier T. (1998) Interaction of vestibular, somatosensory and visual signals for postural control and motion perception under terrestrial and microgravity conditions--a conceptual model. Brain Res Revs. 28:118-135.

49. Mergner, T, Wertheim, A and Rumbereger, A. (2000) Which retinal and extr-retinal information is crucial for Circular Vestion. Archives Italienes de Biologie, 138, 123-138.

50. Miller, E. F., and Graybiel, A. (1966) Magnitude of gravito inertial force, an independent variable in egocentric visual localization of the horizontal. *J. exp. Psychol,* 71:452-460.

51. Mittlestaedt, H.(1996) Somatic Graviception. Biol. Psychol. 42: 53-74.

52. Mittelstaedt, M. L. and Glasauer, S. (1992). The contribution of inertial and substratal information to the perception of linear displacement, Proceedings of XVIIth Bárány Society Meeting. H. Krejcova and J. Dobris, (Eds.). Czechoslovakia, 62:247-263, pp. 102-105.

53. Mittelstaedt, M. L. (1994) Influence of centrifugal force on angular velocity estimation. Proceedings of 18th Barany Society, Uppsala, Sweden, Acta Otolaryngol Supp.

54. Noble, C. E. (1949) The perception of the vertical III. The visual vertical as a function of centrifugal and gravitational forces. J. Exp. Psychol. 39: 839-850.

55. Oman, C.M., Lichtenberg B.K., Money, K.E., and McCoy, R.K., (1986) M.I.T./Canadian Vestibular Experiments on the Spacelab-1 Mission: 4. Space Motion Sickness: Symptoms, Stimuli, and Predictability. Exp.Brain Res. 64:316-334.

56. Page, N. G. R., Gresty, M.A. (1985) Motorist's vestibular disorientation syndrome. J. Neurol. Neurosurg. and Psychiat. 48, 729-735.

57. Paloski, W.H., Black, F.O., Reschke, M.F. (1993) Vestibular Ataxia Following Shuttle Flights: Effect of Transient Microgravity on Otolith-mediated Sensorimotor Control of Posture. Am.J.Otology. 1:9-17.

58. Raj A.K., Kass S.J., & Perry J.F. (2000). Vibrotactile Displays for Improving Spatial Awareness. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, (I), pp 181-184.

59. Robinson, D. A. (1977). Vestibular and optokinetic symbiosis: an example of explaining by modelling. In: Control of Gaze by Brain Stem Neurons, Developments in Neuroscience, Vol. 1. Elsevier/North-Holland Biomedical Press pp. 49-58.

60. Rupert A.H (2000, Mar-Apr) An Instrumentation Solution for Reducing Spatial Disorientation Mishaps. IEEE Engineering in Medicine and Biology,19(2): 71-80.

61. Starr, Mike. (2001) Team Texas High Performance Driving School. 15468 Highway 156,Justin, Texas, 76247.

62. Stockwell, C.W., and Guedry, F.E., (1970) The effects of semicircular canal stimulation during tilting of the subsequent perception of the visual vertical. Acta Otolaryng. (Stockh.), 70:170-175.

63. Tormes, F.R., and Guedry, F.E., (1975) Disorientation phenomena in Naval helicopter pilots. Aviat. Space Environ. Med., 46:387-393.

64. Tribukait, A. (1976) Semicular canal and saccular influence on the subjective visual horizontal during gondola centrifugation. Department of Audiology, Karolinska Hospital, Stockholm, Sweden

65. Wing, C., and Passey, G. E. (1950) The visual vedrtical under conflicting visual and acceleration factors. Joint Project report 20. Tulane University and ONR project NR 143-455.

66. Watt, D., Bouyer, L., Nevo, I., Smith, A. and Yang, T. (1992) What is motion sickness. In B. Cohen, D.L. Tomko, F.E. Guedry, Eds., Sensing and Controlling Motion, New York: Annals of the New York Academy of Sciences, 656: 660-667.